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## Enhancing Battery Lifetime In PV Battery Home Storage System Using Forecast Based Operating Strategies

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### Abstract

An increase of self-consumption from domestic photovoltaic (PV) can be gained by the use of PV battery energy storage systems (PV-BESS). PV-BESS are currently just at the edge of profitability. Intelligent operating strategies might further increase the economy of these systems. This paper presents a novel approach for an operating strategy for PV-BESS which is able to increase the lifetime of lithium-ion batteries in such systems without reducing the self-consumption rate significantly. The operating strategy is evaluated by simulations, using a model of a DC-coupled PV-BESS and real data measurements as model inputs. To enhance the lifetime of the system, the average state of charge (SOC) of the battery is reduced by storing only the amount of energy predicted to be needed during the following night. With the applied approach, begin of night is defined as the point when the residual load becomes negative and accordingly, end of night is defined as the point when the residual load becomes positive again. This strategy is only applied in the summer months to use the full potential of the storage system during the winter. Using this strategy, seasonal effects like high average SOC's during summer will be reduced. For the necessary prediction, perfect forecast (best case) and persistence forecast (worst case) are evaluated to investigate the influence of prognosis inaccuracies. To minimize losses in self-consumption, not only a forecast for the next night will be considered but a variation of forecast periods is discussed. In conclusion, the results show that the application of such an operating strategy can increase battery lifetime significantly while affecting the self-consumption rate only slightly. Consequently, this operating strategy shows a high potential to increase the profitability of a PV-BESS.

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**Keywords:** PV home storage system; operating strategies; lifetime enhancement; self-consumption; battery energy storage system

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## 1. Introduction

This paper presents a novel approach for an operating strategy for PV-BESS which is able to increase the lifetime of lithium-ion batteries in such systems without reducing the self-consumption rate considerably. The operating strategy is evaluated by simulations, using a model of a DC-coupled PV-BESS and real data measurements as model inputs [1].

The growing spread between PV feed-in-tariff and cost of electricity supply from the local grid lead to an incentive to increase self-consumption of PV energy, which can be achieved by the use of PV-BESS [2, 3]. This is why Germany is facing a growing share of PV-BESS [4]. Intelligent operating strategies might increase the economy of PV-BESS.

Lithium-ion batteries have two aging effects, calendar aging and cycling aging. These effects are described in M. Ecker et al. [5]. Ecker et al. figured out that the calendar lifetime as well as the cycling lifetime depend on the average state of charge (SOC). An increase of the lifetime of a lithium-ion based battery system can be achieved by reducing the average state of charge.

Typical operating strategies store the residual load, even if the energy is not needed later on. As a result, the battery might be charged during the day, but not completely discharged during the night. This leads to the effect that the average SOC is unnecessarily high and decreases the battery lifetime. Therefore, an operating strategy is developed which stores only the amount of energy predicted to be needed during the following night.

Distribution system operators use batteries to stabilize the grid, while households aim to safeguard themselves against rising electricity prices, or would like to use more ecofriendly energy and be more independent from energy companies [6]. Different types of battery operating strategies to stabilize the grid are available. These strategies also influence the lifetime of the battery. In [7] different operating strategies which lead to grid stabilization are discussed. Operating strategies with feed-in limitations require forecast for load and radiation to minimize the losses of self-consumption. Fig. 1 illustrates the strategies which are discussed. The influence of grid stabilizing strategies is discussed in [8].

Other concepts focus on Demand Side Management. In times of high solar and wind power generation consumers are encouraged to consume electricity or charge the battery. The operation of PV-batteries combined with appropriate pricing structures, inversely proportional to PV production, can lead to grid relief [9].

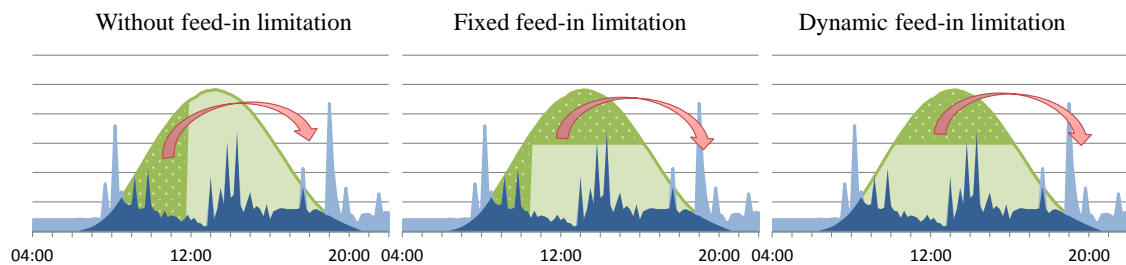


Fig. 1: Different operating strategies for PV-BESS discussed in literature.

### Nomenclature

BESS	battery energy storage systems
DC	direct current
PV	photovoltaic
SOC	state of charge

## 2. Methodology

The developed operating strategy is evaluated by simulations, using a model of a DC-coupled PV-BESS and real data measurements as model inputs. Fig. 2 shows the elements of the DC-coupled PV-BESS. This model is based on a lithium-ion battery storage system with 10 kWh and a 5 kWp PV system. For this model the parameters of SAFT VL45-E lithium-ion cells are used. The lifetime of these cells is relatively high and therefore is not representative for other battery cells in lithium-ion based PV-BESS. This leads to the effect that the average lifespan of typical lithium-ion based PV home storage systems will be lower compared to the model. For example, the PV-BESS in the model has a lifetime of 20 to 30 years. In comparison the PV system from Tesla called “Powerwall” is advertised to have a lifetime of 15 years and 5000 cycles [10]. Nevertheless, the relative statements of the results also apply to other lithium-ion batteries. For systems with a lower lifetime the influence of operating strategies on the economy is higher because of the annuity effect.

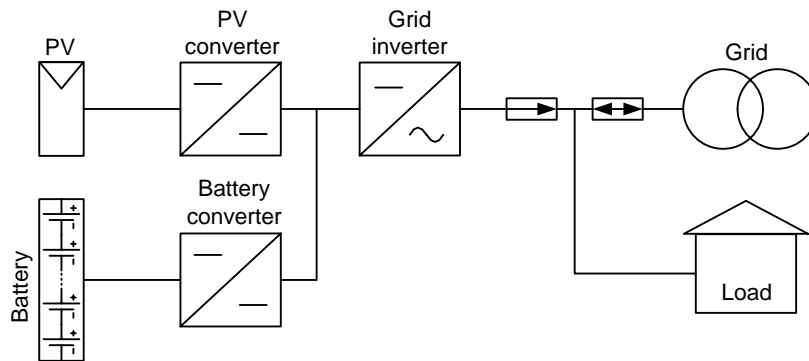


Fig. 2: Model of the grid connected DC-coupled PV-BESS. This model contains a PV generator, two DC/DC converters, one AC/DC converter, the battery energy storage system as well as the household and the grid [1].

The load during night determines a maximum SOC, which corresponds exactly to the amount of energy which is needed during night. With the presented operating strategy, this maximum SOC is not exceeded even though there is more positive residual load available during daytime. The reference point for the determination of the maximum SOC is the beginning of the night. To predict the energy which is needed during night the determination of day and night time is crucial. With the applied approach, the beginning of the night is defined as the point where the residual load becomes negative for the first time and accordingly, end of the night is defined as the point where the residual load becomes positive again. As a boundary condition, the time between these two points should be a least five hours. If the time is less than five hours, the negative residual load is considered as a load drop during the day and not as beginning of nighttime. The five hour boundary is chosen, because the analysis shows that even during summer in Germany there are at least five hours without daylight in the night.

To evaluate the performance of the algorithm and to investigate the influence of forecast errors, the necessary prediction is analyzed in two scenarios: perfect forecast (best case) and persistence forecast (worst case). The persistence forecast uses the assumption that the PV radiation will be the same as the day before and the load will be the same as the load last week on the same day. Both prediction models are compared.

To use the full potential of the storage system during winter, this strategy is only applied in the summer months, where a violation of feed-in limitations is to be expected. Furthermore, the losses of the BESS are taken into account. To evaluate the best strategy for the given PV-BESS the energy throughput during the battery lifespan is calculated. To reduce computational effort, the first year of the PV-BESS operation is simulated and

the determined energy throughput  $E_{year}$  is assumed to apply also to the following years. Based on the known battery aging characteristic, the lifetime  $l_{bat}$  in years is extrapolated. The resulting energy throughput over the battery lifetime  $E_{life}$  therefore results to

$$E_{life} = E_{year} \cdot l_{bat}$$

The energy throughput  $E_{life}$  is used because this value can determine how good an existing PV-BESS is used. PV-BESS which are used in a more effective way can gain more revenue. The annual energy throughput has a higher influence on the revenue than the battery lifetime due to scale and annuity effects. Scale effects lead to lower costs for future PV-BESS. This leads to an incentive to invest in cheaper and less long-lasting PV-BESS. Annuities lead to the effect, that payments in the future are less valuable than payments in the present, due to the interest rate. BESS with a long battery lifetime generate more revenues in the future, which are less valuable than revenues in the present. This is why the energy throughput has a higher influence on the economy than the lifetime.

### 3. Results

Fig. 3 illustrates the state of charge characteristic during a week in July. The solid curve shows the SOC behavior with a simple self-consumption maximizing operating strategy (referred to as MAX\_SOC below) and the dashed curve the SOC behavior when the presented operating strategy is applied (referred to as MIN\_SOC below). Using the MAX\_SOC strategy the average SOC from July 1<sup>st</sup> to July 6<sup>th</sup> is 68 %, while the use of the MIN\_SOC strategy reduces the average SOC to 29 %, so less than half of the original value. The annual average SOC using the MAX\_SOC strategy is 30 %, whereas the annual average SOC using the MIN\_SOC strategy is 17 %. Due to the reduction of the average SOC, the lifetime of the battery is enhanced by around six and a half years based on the model assumptions. The depicted results are based on a perfect forecast, where the battery always reaches exactly an SOC of 0 % at the end of the nightly discharge.

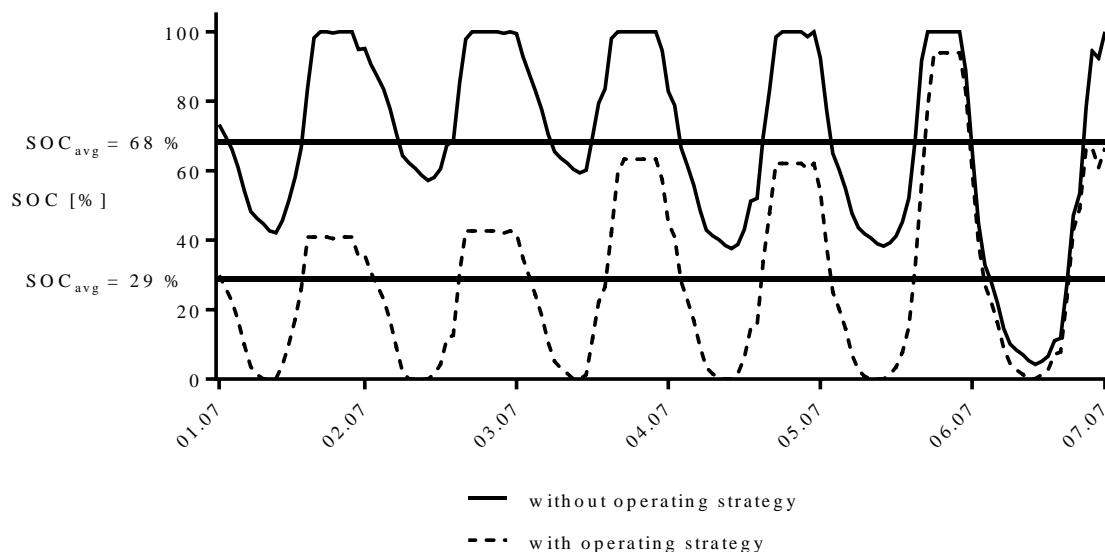


Fig. 3: The state of charge of the PV-BESS with and without an operating strategy, from July 1<sup>st</sup> to July 6<sup>th</sup>.

Two additional analyses are shown in the following. First, the influence of the prognosis horizon is analyzed. In some cases it is possible that an excess of PV energy on one day is refused to charge the battery but could be used on the next day or the day after the next day due to shortcoming of PV generation on those days. Therefore, a one day prognosis is compared to a two and three day prognosis. Second, the influences of forecast errors are discussed. The energy throughput  $E_{life}$  is used to evaluate the different effects.

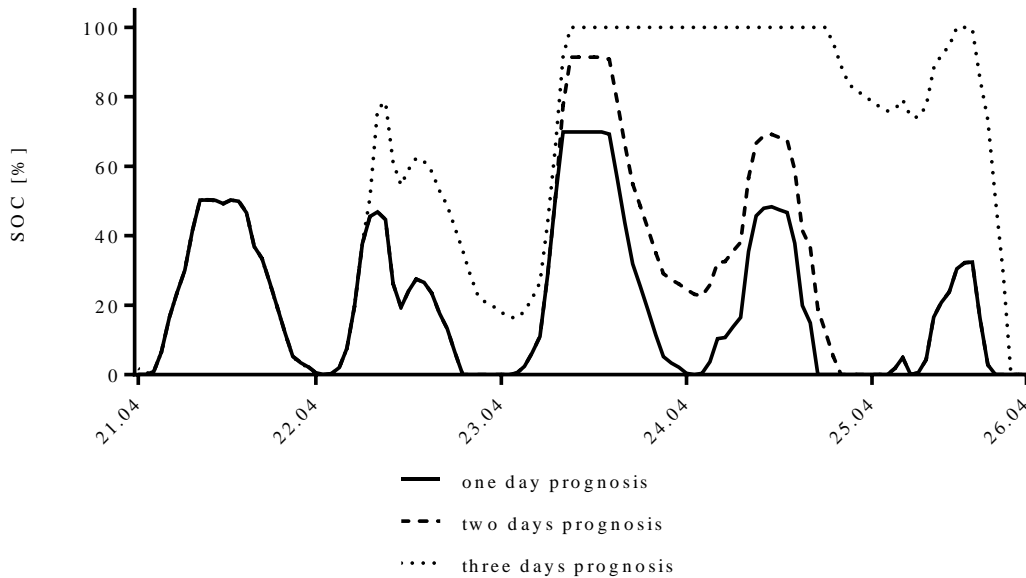


Fig. 4: Comparison of different forecast horizons for one, two and three day prognosis during April 21<sup>st</sup> to April 25<sup>th</sup>.

Fig. 4 shows the comparison of different forecast horizons. The solid line represents an operating strategy which is based on the forecast for the following night. The bold dashed line applies the forecast of the two following nights, and the third line represents the state of charge when a three day forecast is applied. In the selected example the SOC behavior is changing at multiple points by the use of different forecast horizons. At these points, energy is stored over two or three days to satisfy the energy needs of the following nights. The different trends of the SOC as shown in Fig. 4 are analyzed based on a perfect forecast.

Fig. 5 a) illustrates the average SOC for the different prognosis horizons. The average SOC is strongly related to the battery lifetime. For the necessary prediction, perfect forecast (best case) and persistence forecast (worst case) are evaluated to investigate the influence of prognosis inaccuracies. The persistence prognosis is only applied for a one day prognosis. Fig. 5 b) and c) show the lifetime and annual energy throughput resulting from the different operating strategies. There is a strong correlation between battery lifetime and annual energy throughput. The throughput increases while the lifetime decreases. The highest annual energy throughput is reached when the MAX\_SOC strategy is used. This is obvious, because in this case energy is stored as soon as positive residual load occurs and the battery has not reached yet the maximum SOC. If the three days prognosis is used the annual energy throughput is almost the same. In this case the lifetime of the battery is the lowest, compared to the other prognosis strategies. The lifetime of the three days prognosis is the lowest because of the calendar and cycling ageing effects of lithium-ion batteries. An enhanced prognosis horizon leads to an increased

average SOC as shown in Fig. 5 a). The aging effects depend on the average SOC. A higher average SOC leads to higher calendric ageing as described in [5]. If the persistence prognosis is used, the predicted maximum SOC's differ from the optimum predicted by the perfect prognosis, due to forecast errors. If the maximum SOC is overrated by the persistence prognosis, sometimes this SOC cannot be reached during day because there is not enough residual energy available. If the maximum SOC is underrated the possibility that the maximum SOC can be reached during the day is higher. This is why in this case the annual energy throughput is lower, due to prognosis inaccuracies. Therefore, if the persistence prognosis is used the battery lifetime is the highest because the battery is not used as much over the year. Nevertheless, Fig. 5 d) illustrates the resulting total energy throughput for the different operating strategies: although the three days prognosis is able to reach approximately the same annual energy throughput as the MAX\_SOC strategy, the loss of battery lifetime leads to the lowest overall energy throughput of all prognosis based strategies. The highest energy throughput over the battery lifetime is reached with the one day prognosis strategy. Regardless of which strategy is used, all strategies have significantly higher energy throughputs compared to the case of the MAX\_SOC strategy. The persistence prognosis shows the highest lifetime expectancy. This is mainly related to a lower energy throughput due to forecast errors. Nevertheless, the overall performance is very close to the best value, achieved by the perfect prognosis.

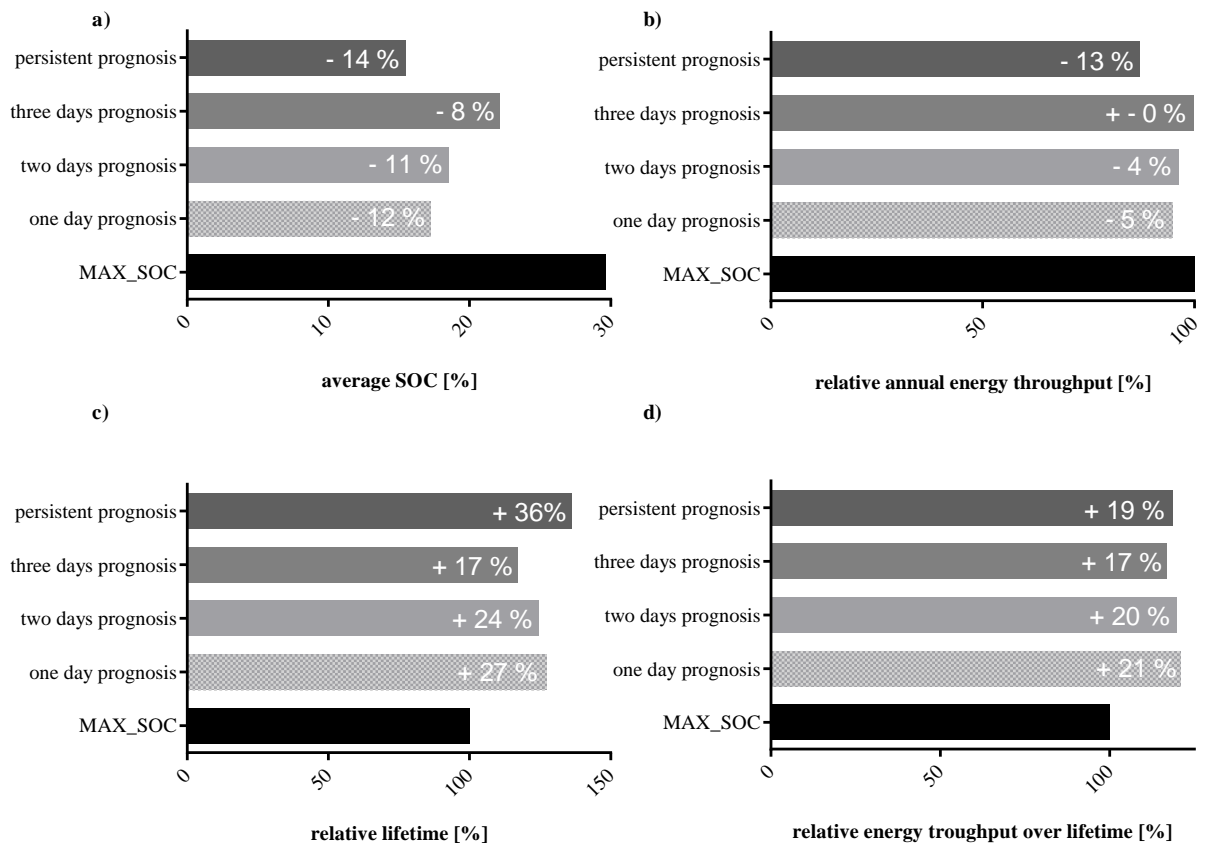


Fig. 5: Energy throughput and lifetime comparison of the different operating strategies.

In the following, the influence of an offset on the predicted target SOC will be discussed. The predicted target SOC might not be the best SOC regarding the energy throughput, due to the calculation of the losses of the BESS. However, not all losses can be calculated exactly during prognosis, because the losses depend on the SOC. The SOC determines the voltage of the BESS and therefore influences the efficiency of the converter. The converter is responsible for a big part of the losses of the BESS. The total energy throughput could be higher by using an offset. When the offset is applied the selected maximum SOC is set higher or lower than the predicted maximum SOC. For example, if the predicted target SOC is 60 % and the offset is plus three percent the selected target SOC is 63 %. The offset with the highest energy throughput by the perfect prognosis is calculated to +2 %. This leads to the effect that the chosen maximum SOC is set two percent higher than the SOC which is calculated based on the strategy. The depicted result is shown in Fig. 6. Due to prognosis inaccuracies when persistence prognosis is used, an additional offset is necessary to reach the highest throughput. In this simulation an offset of six percent leads to the highest energy throughput. Fig. 7 illustrates the result for the persistence prognosis.

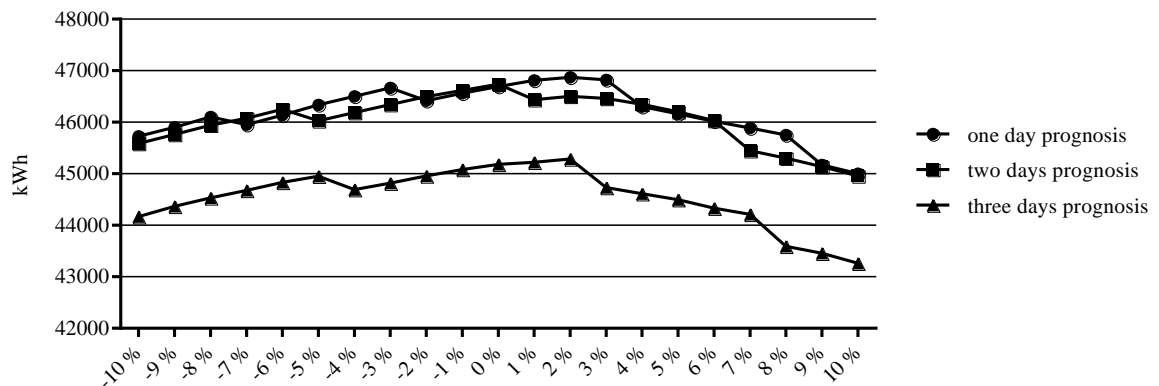


Fig. 6: Total throughput over an offset of the maximum SOC for perfect prognosis. The offset with the highest throughput is used as the reference value. In case of the perfect prognosis the offset is plus two percent.

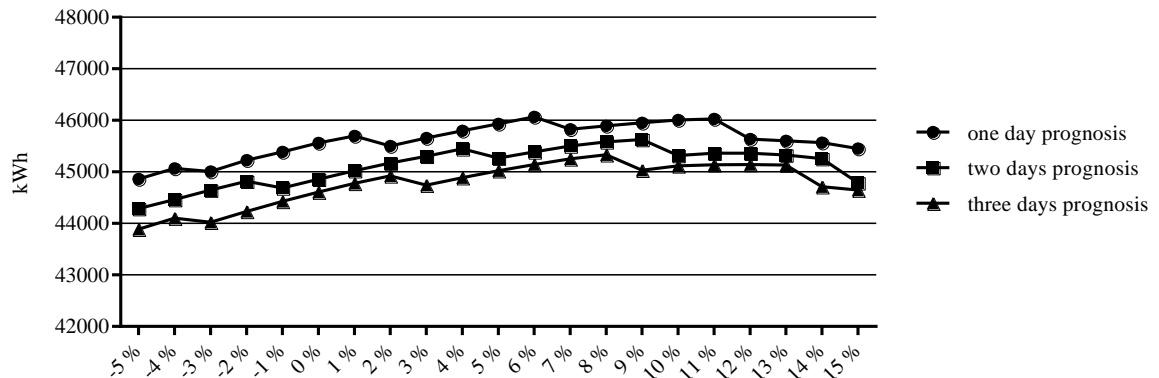


Fig. 7: Total throughput over an offset of the maximum SOC for the persistent prognosis. The offset with the highest throughput is used as the reference value. In case of the persistent prognosis the offset is six percent.

Combination of the offset with other strategies will be discussed below. If a fixed SOC limit is set, the battery lifetime can be enhanced. Therefore the maximum SOC limit was calculated so that the energy throughput over the complete battery lifetime is the highest. If the maximum SOC limitation is set to 67 % the operation strategy of direct self-consumption leads to the highest energy throughput over the complete battery lifetime. If we compare this result with the discussed results we can see that this strategy leads to a higher total energy throughput than with the one day perfect prognosis. Fig. 8 shows the comparison of different strategies. An even higher energy throughput over the battery lifetime can be gained by the combination of the SOC limitation to 67 % and the perfect prognosis strategy. The combination of the limitation to 67 % and the persistence prognosis strategy leads to a higher energy throughput than the one day persistence prognosis. Nevertheless, the combination of the persistence prognosis and the limitation to 67 % leads to a lower energy throughput than solely the limitation. The strategy shows high potential to increase the economy of PV-BESS, especially when a curtailment of the PV system is required and better forecast strategies are used.

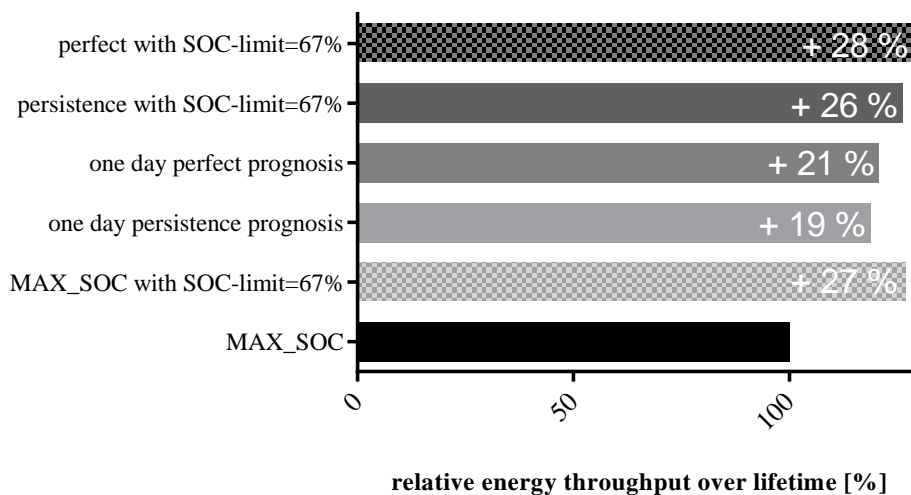


Fig. 8: Total energy throughput over the battery lifetime of different combinations of operating strategies.

#### 4. Discussion and Conclusion

This paper presents a novel approach for an operating strategy for PV-BESS which is able to increase the lifetime of lithium-ion batteries in such systems without reducing the self-consumption rate significantly. Hereby, the strategies are compared to a simple self-consumption maximizing strategy of the PV-BESS. To enhance the lifetime of the system, the average state of charge is reduced by storing only the amount of energy predicted to be needed during subsequent nights. For the necessary prediction, perfect forecast (best case) and persistence forecast (worst case) are evaluated to investigate the influence of prognosis inaccuracies. To minimize the reduction of self-consumption, not only a forecast for the next night is considered, but variations of different forecast periods are discussed. If the forecast horizon is expanded to three nights instead of one night, the yearly energy throughput of the BESS can be increased. In addition, the average SOC of the three day prognosis is higher. While the overall self-consumption rate can be slightly increased, the two aforementioned effects lead to a shorter lifetime of the BESS. Using the presented forecast-based operating strategy, seasonal effects like high average SOC during



summer will be reduced. In conclusion, the results show that the application of such an operating strategy can significantly increase battery lifetime while only slightly affecting the self-consumption rate. Furthermore, the results show that a forecast over three days leads to a significantly lower energy throughput over the battery lifetime compared to a one or two day forecast.

The investigation shows that a one day forecast is in most cases the optimal choice. Alternatively, the use of a fixed SOC limit and its potential to reduce the aging of the battery are analyzed. The combination of the one day forecast and a fixed SOC limit increases the energy throughput over lifetime and can influence the efficiency of a PV-BESS in a positive way. The combination of both kinds of strategies leads to the highest energy throughput over the battery lifetime.

Consequently, this operating strategy shows a high potential to increase the profitability of a PV-BESS. Further studies of the combination with curtailment strategies as well as a monetary evaluation will be conducted. The monetary evaluation should validate the results because the energy throughput is just a proxy. The influence of these strategies on the energy flows of the PV-BESS could lead to different monetary results.

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